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Hot, Wide, Continental Back-arcs Explain Earth's Enigmatic mid-Proterozoic Magmatic and Metamorphic Record

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Abstract Higher than average thermobaric ratios (temperature/pressure) of metamorphic rocks and abundant 'dry' ferroan magmatism including massif anorthosite suites are two enigmatic features of the mid-Proterozoic (1.85–0.85 Ga) that have unclear origins. It has been proposed that elevated mantle temperatures due to insulation under the Columbia supercontinent, and/or to plate slowdown, combined with thin lithosphere, led to high continental geothermal gradients, high-temperature metamorphism, and an increase in dry, ferroan magmatism. Geodynamic modelling predicts that continental subduction zones at mid-Proterozoic mantle potential temperatures (80–150°C hotter than at present) would exhibit key differences to the Phanerozoic, critically, extensive slab rollback combined with greater volumes of decompression melting of the asthenosphere would lead to wide regions of back-arc magmatism. We posit that these hot, wide continental back-arcs can effectively explain the abundance of ferroan magmatism, anorthosite suites, and high T/P metamorphism. Our model negates the need for extra mantle heating from supercontinental insulation or plate slowdown and shows that the tectonic regime of the mid-Proterozoic was a transitional phase between those of the Archean (likely comprising peel-back tectonics and episodic subduction) and the Phanerozoic (comprising deep continental subduction), and which could have resulted solely from secular cooling of the mantle.

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1 Introduction

It is generally agreed that the dominant tectono-magmatic processes of continental crust formation must have changed through Earth history, particularly as they are influenced by changing mantle temperatures (see Figure 1a); however, whereas much attention has been focused on Archean processes, the Proterozoic has been somewhat neglected. Indeed, the geological record of the Proterozoic, and the mid-Proterozoic in particular (1.85–0.85 Ga), exhibits many enigmatic features that distinguish it from those of the Phanerozoic and Archean, making it Earth's 'Middle Age' (*Cawood and Hawkesworth*, 2014). These include an apparent high in thermobaric ratios recorded in metamorphic rocks (*Brown and Johnson*, 2018, 2019, Figure 1b), and intrusion of voluminous massif anorthosite suites (*Ashwal and Bybee*, 2017, Figure 1c). It has been proposed that many of these features can be explained by the combined influence of mantle heating due to supercontinental insulation (*Brown and Johnson*, 2018), a slowdown in plate motions (*O'Neill et al.*, 2022), and a temporary return to a single-lid tectonic regime following an attempted start of plate tectonics in the Paleoproterozoic (*Stern*, 2020). However, *Roberts et al.* (2022) questioned the necessity for supercontinental insulation and demonstrated that plate tectonics, albeit dominated by accretionary orogenesis, was active throughout the mid-Proterozoic. Although *Roberts et al.* (2022) argued that the metamorphic and magmatic record resulted from transitional changes in geodynamics due to secular cooling of the mantle, they do not present a direct explanation for magmatic features such as the abundance of massif anorthosites, or an apparent increase in A-type granitic magmatism. Here, we address these issues specifically. We make use of published geodynamic numerical models of subduction zones and show that several features common to models conducted at mid-Proterozoic mantle potential temperatures (80–150°C hotter than at present) can effectively explain the geological record of this period. Our model negates the need for mantle heating due to supercontinental insulation and/or plate slowdown.

2 Data

Along with anorthosite-mangerite-charnockite suites (*Ashwal*, 2010; *Ashwal and Bybee*, 2017), and other as-

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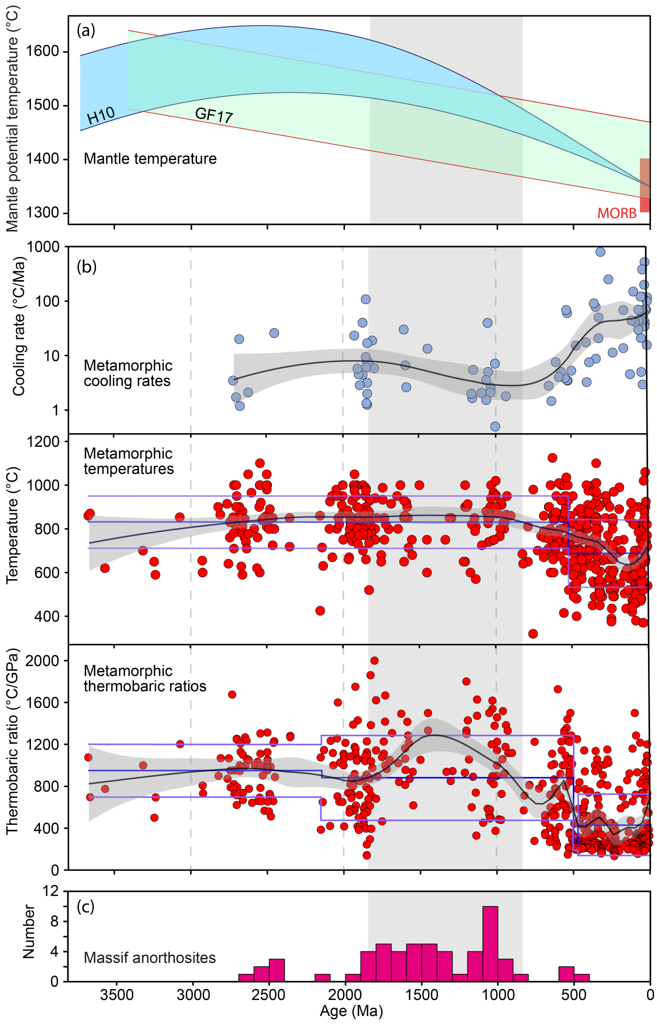

Figure 1 – **(a)** Estimates of mantle potential temperature through time; H10 from *Herzberg et al.* (2010), and GF17 from *Ganne and Feng* (2017). MORB = Mid-Ocean Ridge Basalt. **(b)** Metamorphic record presented as cooling rates (dataset of *Brown et al.*, 2022), temperatures and thermobaric ratios through time (dataset of *Brown and Johnson*, 2018, 2019). Grey curves are LOWESS (locally weighted scatterplot smoothing) estimates of the mean trends through time; blue lines demonstrate the results of conjugate partition recursion which is used to find statistical changes in the mean values (from *Brown et al.*, 2022). **(c)** Frequency of massif anorthosites, binned at 100 Myrs (*Ashwal and Bybee*, 2017). Grey bar represents the mid-Proterozoic time-interval (1.85–0.85 Ga).

sociated ferroan magmatism such as rapakivi suites (*Rämö and Haapala*, 1995; *Vigneresse*, 2005), it has been argued that the mid-Proterozoic comprised more abundant "non-arc" (*Liu et al.*, 2017, 2019) or A-type magmas in general (*Stern*, 2020). Estimating volumes of magmatic products in deep time is fraught with issues of sampling and preservation bias; nonetheless, large global geochemical databases are now commonly used to address secular changes at a global scale. To address secular change in continental magmatism, we interrogate the geochemical composition of felsic rocks by utilising the published dataset of *Gard et al.* (2019), with the addition of data from 155 sources (see supplementary file for details). We filtered the data for $57 < SiO_2 < 72$ wt%, binned this subset into 100 Myr intervals, and plot as interquartile ranges. Key plots are shown in Figure 2, and additional plots are available on figshare (https://doi.org/10.6084/m9.figshare.c.6328883.v1).

3 Mid-Proterozoic Felsic Geochemical Composition

There are several distinctive features of the felsic igneous record that occur broadly between ca. 1.9–1.8 Ga and ca. 1.0–0.8 Ga (Figure 2), i.e. the informal period of the mid-Proterozoic. These include a marked decrease in La/Yb, Sr/Y, and Eu/Eu*, and an increase in K_2O/Na_2O, Rb/Sr and Fe-number (FeOt/(FeOt+MgO). ASI (Aluminium Saturation Index) has no distinct change, and MALI (Modified Alkali Lime Index) has a subtle increase suggesting an increase in alkalinity of granites during this period. The rapid decrease in Sr/Y at ca. 1.9 Ga was previously highlighted by *Tamblyn et al.* (2022), and ascribed to increasing volumes of residual plagioclase and decreasing volumes of residual garnet during granite formation. This mechanism can also explain secular changes in Rb/Sr, Eu/Eu* and K_2O/Na_2O, given the compatibility of Sr, Eu and Na in plagioclase. The change in Fe-number, a result of both decreasing Mg and increasing Fe contents (Figure S1; https://doi.org/10.6084/m9.figshare.c.6328883.v1), indicates an enrichment in ferroan geochemical signatures (Figure 2). Ferroan granitoids are synonymous with A-type signatures (*Frost et al.*, 2001; *Frost and Frost*, 2010), and it can be seen that A-type indicators such as high Zr+Nb+Ce+Y (i.e. elevated HFSEs) are also notably abundant in the mid-Proterozoic.

Ferroan granitoid formation is known to typically involve large degrees of plagioclase fractionation (*Frost and Frost*, 2010), which leads to the obvious question: does a transition from dominantly magnesian magmatism to dominantly ferroan magmatism explain overall trends in mid-Proterozoic granite composition? In Figure 2, a plot of ferroan vs. magnesian granitoids clearly indicates a change from 50% in the mid-Proterozoic to only 30% at <1 Ga. However, dividing the data into ferroan and magnesian compositions shows that both varieties exhibit lower Sr/Y through the mid-Proterozoic. Therefore, there is both a systematic reduction of average Sr/Y contents across granite types, as well as an increase in ferroan (A-type) signatures through the mid-Proterozoic. These observations can be explained by: 1) increasing residual plagioclase compared to that of garnet, requiring magma generation at shallower depths and/or under higher geothermal gradients (e.g. *Alonso-Perez et al.*, 2009; *Moyen*, 2009); 2) smaller degrees of melting, leading to elevated incompatible element abundance (e.g. HFSEs); and/or 3) high-temperature melting of residues from previous magma extraction, which also elevates the HFSE concentrations such as Zr (*Collins et al.*, 2020).

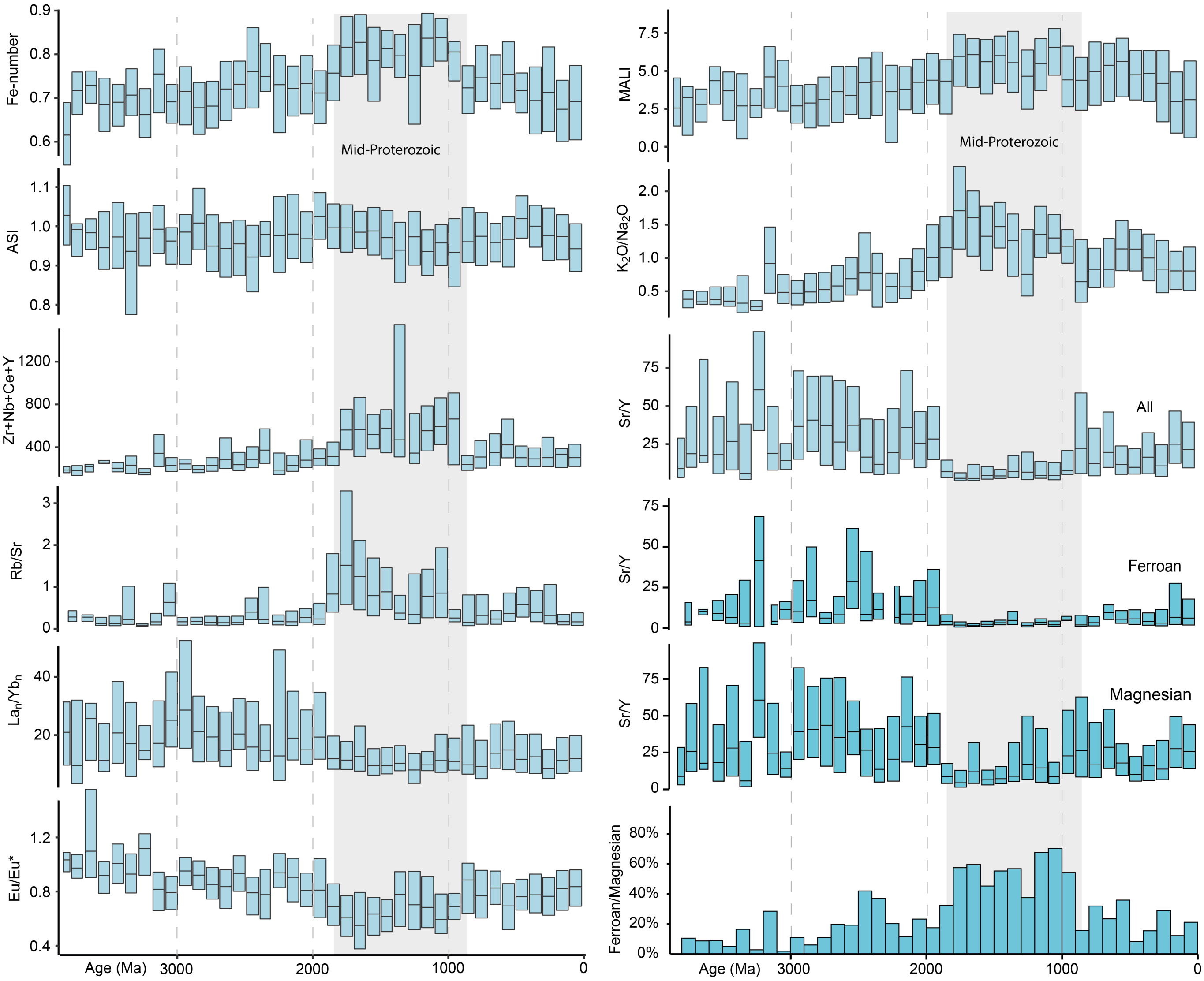

Figure 2 – Secular trends in felsic igneous geochemistry, presented as boxplots without whiskers, binned at 100 Myrs, see main text for source of data. Eu/Eu* = chondrite normalised Eu/(Sm*Gd)$^{0.5}$, Fe-number = FeOt/(FeOt+MgO), MALI = Modified Alkali Lime Index, and ASI = Aluminium Saturation Index (*Frost et al.*, 2001).

4 Geodynamics of mid-Proterozoic Subduction Zones

Mantle temperature plays a fundamental role in controlling the geodynamics at convergent plate boundaries, through its influence on the density and rheology of the lithosphere and asthenosphere. The effect of elevated mantle potential temperature (Tp) on the style of Precambrian subduction has been studied in detail using numerical modelling by *Sizova et al.* (2010), *Fischer and Gerya* (2016), and *Perchuk et al.* (2019). Although the models encompass contrasting temperatures and input parameters, a number of key features can be gleaned that apply to an elevated mantle Tp of around ΔT 80–120 °C, i.e. that of the mid-Proterozoic. These are: 1) extensive and rapid rollback of the subducting lithosphere; 2) a greater width between the back-arc and trench; 3) voluminous decompression melting of asthenospheric mantle; and 4) melting of both basalt and lower continental crust in response to ascent of this asthenospheric mantle. These can broadly be considered a result of increased melt-weakening of the lithosphere, a lower density contrast between oceanic lithosphere and asthenosphere, and increased asthenospheric temperatures. Figure 3a and 3b shows a reference modern-day (ΔT 0 °C) model of subduction with comparison to a model run at ΔT 100 °C (from *Sizova et al.*, 2010), and these are simplified for purposes of comparison in Figure 3c and 3d. A modern-day retreating slab will lead to formation of a back-arc region that hosts decompression melting of the mantle that is dominantly below the 4% threshold for melt extraction (*Sizova et al.*, 2010). New basaltic oceanic crust is produced in a region of lithosphere thinned by melt-weakening, and host to rising asthenosphere. More proximal to the trench is a continental arc intruded by fluid-fluxed melts of mantle material. At ΔT 100 °C, the extent of slab retreat and upper-plate extension is greater than the ΔT 0 °C reference model. Higher mantle temperatures over a wide back-arc area lead to decompression melting exceeding the melt extraction threshold (4 wt%) across this wide back-arc region; this produces voluminous flood-basalt type (i.e. tholeiitic)

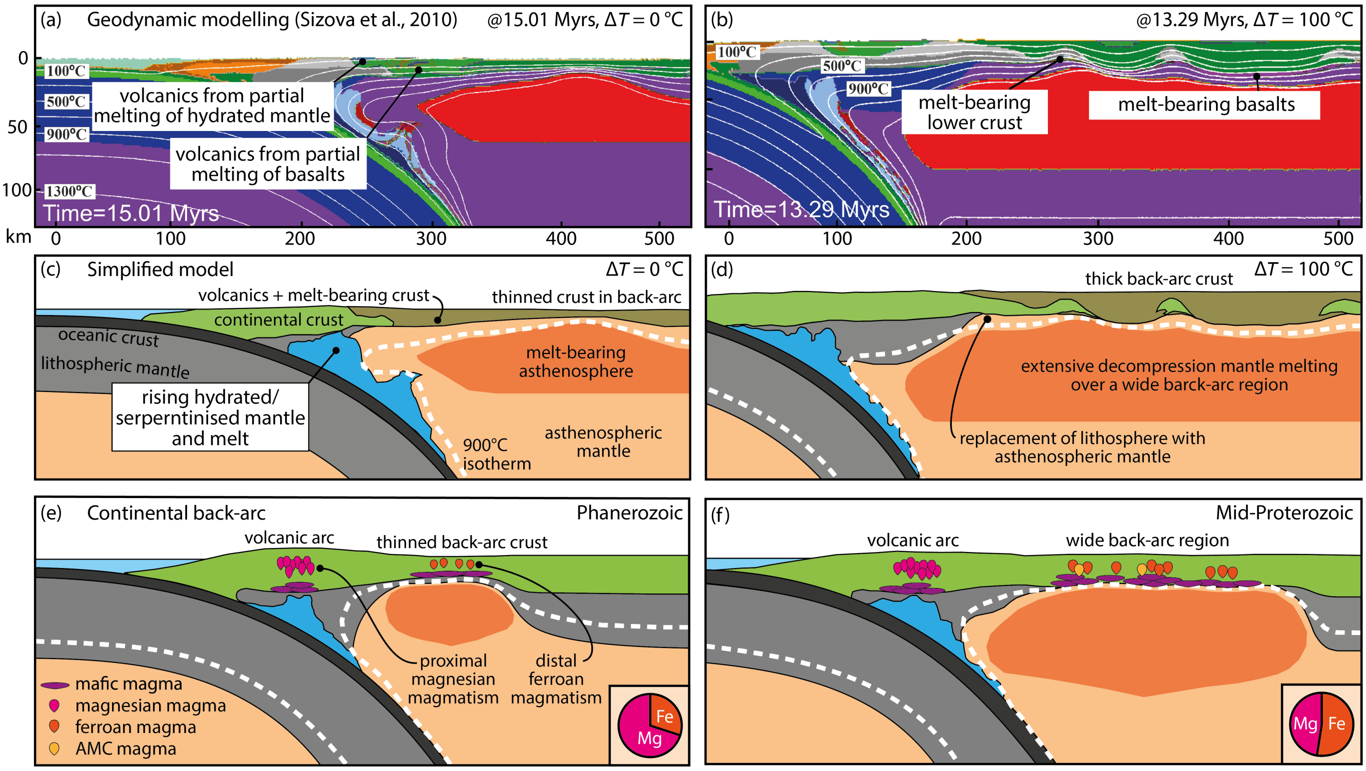

Figure 3 – **(a, b)** Numerical models of ocean-continent subduction zone geodynamics by *Sizova et al.* (2010), run at ΔT = 0 °C **(a)** and 100 °C **(b)**; these are snapshots taken at the quoted run-times of 15.01 and 13.29 Myrs, respectively. Reproduced from *Sizova et al.* (2010), with permission from Elsevier. **(c, d)** Simplified versions of the geodynamic models in **(a)** and **(b)**. **(e)** A modern subduction zone combining elements of numerical modelling (*Sizova et al.*, 2010; *Vogt et al.*, 2012) with that of the 'proximal I-type, distal A-type' Lachlan Orogen model of *Collins et al.* (2020). **(f)** Hypothesised ocean-continent subduction zone geodynamics that would exist with mid-Proterozoic Tp. Pie charts show the ratio of magnesian to ferroan magmatism, estimated from the Ferroan/Magnesian ratios in Figure 1

magmatism across this region. In both the modern-day and ΔT 100 °C models, lithospheric mantle is removed across the back-arc region by convective thinning (*Currie et al.*, 2008), bringing asthenospheric mantle and the 900 °C isotherm close to or in contact with the lower crust.

Modern subduction zones are cyclic in nature (e.g. *Haschke et al.*, 2002; *DeCelles et al.*, 2009), and can be divided into retreating and advancing modes whereby the trench is in net retreat or advance compared to a fixed point on the upper plate (*Cawood et al.*, 2009). Modern examples of retreating and advancing subduction zones are exemplified by those of the Western Pacific and the Andes, respectively. The implication is that Phanerozoic subduction zones widely vary in architecture, with some comprising oceanic basins behind the volcanic arc, and others comprising significantly thickened and elevated continental crust. Whether Proterozoic subduction zones exhibit such contrasting architecture has not been constrained by modelling, but to date, existing geodynamic models are dominated by subduction zones in retreating mode (*Sizova et al.*, 2010; *Fischer and Gerya*, 2016; *Perchuk et al.*, 2019). Based on the observations that at elevated mantle potential temperature: 1) subduction zone margins are dominated by slab rollback and upper plate extension; 2) lithosphere is removed over a broader region of back-arc crust; and 3) asthenospheric melt formation is also much greater in both volume and spatial extent, we can make several hypotheses about the behaviour of Proterozoic subduction zones (Figure 3c-d). Figure 3e shows a simplified version of a Phanerozoic subduction zone for comparison with our Proterozoic model. This comprises a main volcanic arc dominated by magnesian (I-type) magmatism that is ultimately sourced from volatile-fluxed hydrous mantle melting, and a back-arc region hosting less voluminous ferroan magmatism that results from extensive fractional crystallisation and/or anatexis of basaltic underplate under drier conditions. This concept of proximal magnesian and distal ferroan magmatism across a convergent margin is well known from modern retreating or cyclical accretionary orogens such as the Tasmanides of SE Australia (*Collins et al.*, 2020). The contrasting volumes of the coastal batholiths of North America (e.g. *DeCelles et al.*, 2009) with that of the inland Basin and Range magmatism (e.g. *Liu*, 2001), provides another useful analogue of proximal magnesian and distal ferroan subduction zone magmatism.

The mid-Proterozoic model (Figure 3f) comprises a wider volcanic arc that is still dominated by magnesian magmatism. Although speculative, we suggest that wider and thinner volcanic arcs resulting from rapid slab rollback and upper plate extension befit both the geodynamic modelling and the compositional signatures (i.e. lower Sr/Y). Furthermore, this is in stark contrast to thick continental arcs of the Phanerozoic such as the Andes that require strong plate coupling and high convergence rates (*Sobolev and Babeyko*, 2005). Behind the volcanic arc, a wide (»100 kms) back-arc region is formed that hosts voluminous basaltic underplating resulting from decompression melting of the asthenosphere. Felsic magmatism in this back-arc region can result from extensive fractional crystallisation and/or remelting of this underplated basalt (that in turn is derived from small degrees of decompression mantle melting), i.e. the tholeiite connection proposed for mid-Proterozoic magmatism in North America (*Frost and Frost*, 1997, 2010). Moho temperatures across the back-arc are high enough to induce partial melting of the lower crust; therefore, felsic ferroan magmatism can also be derived from partial melting of the lower crust that is residual from previous melt extraction events (*Collins et al.*, 1982; *Landenberger and Collins*, 1996). The back-arc magmatism may be distributed in distinctive magmatic belts where deep-seated structures control magma ascent; these may be far from the active arc and trench, and critically, far from any arc-associated lithological assemblage that may be preserved in the geological record.

5 Implications of Hot, Wide Continental Back-arcs

Phanerozoic back-arc regions, including both those that are dominantly advancing (i.e. the North American Cordillera and Andes), and those that are dominantly retreating (i.e. west Pacific), comprise wide (hundreds of kilometres) regions of elevated heat-flow, thin lithosphere ($\sim$35–40 km), and have Moho temperatures of $\sim$800 °C (*Hyndman et al.*, 2005). Magmatism is typically small in volume inboard of the main volcanic arc. In contrast, our model of mid-Proterozoic wide continental back-arcs comprises: 1) a much greater extent of felsic back-arc magmatism, and 2) magmatism forming under higher geothermal gradients when compared to the Phanerozoic (due to elevated mantle temperatures under 'normal' crustal thickness). These features explain both compositions indicative of increased plagioclase stability across all granitoids and an increased ratio of ferroan to magnesian magmatism across the convergent margin as a whole. Our model explains the occurrence of ferroan back-arc magmatism that is distal to the convergent margin and main volcanic arc, and thus explains the 'anorogenic' appearance of many mid-Proterozoic magmatic suites (e.g *Haapala and Tapani Rämö*, 1992; *Anderson and Morrison*, 2005). Although we point out that describing mid-Proterozoic ferroan suites as distal expressions of convergent margin activity is not new (e.g. *Åhäll et al.*, 2000; *Bickford et al.*, 2015).

Several other enigmatic features of the mid-Proterozoic can also be explained by our model. For example, massif anorthosite-mangerite-charnockite (AMC) complexes are often associated with ferroan magmatism and are most prevalent throughout the Proterozoic (Figure 1c). Although the genesis of AMC suites has been widely debated, their formation can be ascribed to a distinctive set of processes, most simply described as protracted and polybaric fractionation of mafic magmas that have ponded at the Moho at depths of $\sim$30–40 km (*Ashwal and Bybee*, 2017). Although the tectonic settings in which AMC suites form have been debated, many workers favour an active margin setting (*Ashwal and Bybee*, 2017; *Slagstad et al.*, 2018, 2022), although some examples clearly fall within zones of continental collision (e.g. the Grenville Province *Indares*, 2020). We propose that the continental back-arcs of the mid-Proterozoic were ideal settings for generating massif AMC suites since they would have allowed for protracted mafic underplating in areas of mantle upwelling across wide back-arc regions. This is further supported by *O'Neill et al.* (2022) having argued that the stratified Proterozoic crust had a greater ability to trap mid-crustal intrusions than the Phanerozoic and Archean.

The metamorphic record can be expressed as thermobaric ratios (temperature/pressure; T/P) achieved during peak metamorphism, and such compilations can potentially provide insight into secular changes in behaviour of the lithosphere at collisional plate boundaries through time (*Brown and Johnson*, 2018, 2019; *Holder et al.*, 2019). Although limited in sample size, it can be seen that the mid-Proterozoic metamorphic record exhibits elevated thermobaric ratios when compared to the Phanerozoic and the Archean (Figure 1b). This rise is in part due to the lack of blueschist-facies (low T/P) metamorphism between 1.8 and 0.8 Ga, a fact that may be biased by preservation and/or formation (*Palin et al.*, 2020); however, despite this caveat, higher thermobaric ratios can potentially be explained by secular mantle cooling and the resulting influence on orogenesis. *Spencer et al.* (2021) postulated that Proterozoic orogens were hot and thin as a result of elevated mantle heat flow. Here, we build upon this supposition with our proposition of wide continental back-arcs. *Hyndman* (2019) demonstrated that the collision of back-arc regions provides the necessary heat for Barrovian metamorphism, as lower crustal temperatures at $\sim$35 km depth are significantly elevated beyond stable continental crust (typically 400-500 °C). Given that mid-Proterozoic back-arc crust was likely even hotter ($\sim$900 °C at the Moho) over wide areas (Figure 3e), collisional belts involving these back-arc areas, such as the Grenville, Musgrave-Albany-Fraser and Rayner-Eastern Ghats orogens, would easily attain very high temperatures. In addition, intrusion of high-heat-producing granitoids can increase crustal heat flow and contribute to regional metamorphism, which is a common feature of many Proterozoic orogens of Australia (e.g. *Morrissey et al.*, 2014; *Korhonen and Johnson*, 2015). Thus, we speculate a two-fold consequence of our model that may have contributed to the apparent prevalence of high T/P metamorphism in the mid-Proterozoic: 1) pre-collisional lower crustal geotherms were high (>850 °C at ∼35 km), and 2) the intrusion of ferroan (and high-heat producing) magmas produced broad regions of highly radiogenic middle crust.

6 Is Supercontinental Insulation Required?

High metamorphic thermobaric ratios, the abundance of anorthosite magmatism, and granite composition indicative of high geothermal gradients have previously been speculated as a consequence of increased mantle heating below the mid-Proterozoic Columbia supercontinent (*Cawood and Hawkesworth*, 2014; *Brown and Johnson*, 2019; *Tamblyn et al.*, 2022; *Zou et al.*, 2023). *Roberts et al.* (2022) questioned whether this additional mantle heating was necessary, and critically, highlighted that several of these 'indicators' of mantle heating appear in the geological record before the Columbia supercontinent fully amalgamated. Of note, granite compositions show a very distinct change at ca. 1.9 Ga (Figure 2; *Tamblyn et al.*, 2022), which is arguably too early to be caused by mantle warming from the Columbia supercontinent that amalgamated at 2.0–1.6 Ga. Since mantle heating due to the thermal blanketing effect of a supercontinent is dependent on the architecture of the surrounding subduction zones (*Lenardic et al.*, 2011), we argue that the application of this model to the mid-Proterozoic should remain speculative until a detailed study of mantle heating in relation to specific paleogeographic reconstructions is conducted. We also note that there is no record of increased LIP (Large Igneous Province) activity during the mid-Proterozoic (*Condie et al.*, 2021). While we do not discount the prospect of some degree of subcontinental mantle warming due to the formation of Columbia, we hypothesise that the expansive formation of hot continental back-arcs alone can adequately explain the mid-Proterozoic's enigmatic geological record. However, since sub-continental mantle warming would also potentially increase the ambient temperature of back-arc regions, we note that these processes, if present, would have occurred in tandem.

7 Secular Geodynamic Transitions

The nature of Archean tectonics is widely investigated and debated, and is not the focus of this study; however, to understand the mid-Proterozoic, it is pertinent to discuss what came before. Although still a vigorously debated topic, several recent studies agree that some form of stagnant-lid tectonics transitioned, possibly through episodic subduction and peel-back tectonics in the mid- to late Archean, to a sustained global subduction network by the late-Archean to early Proterozoic (*Cawood et al.*, 2018; *Capitanio et al.*, 2019; *Chowdhury et al.*, 2020; *Palin et al.*, 2020; *Condie*, 2021; *Brown et al.*, 2022). We suggest that the mid-Proterozoic is a further transitional phase of geodynamics, comprising truncated hot collisional orogens (*Sizova et al.*, 2014; *Spencer et al.*, 2021) and subduction zones with hot, wide, continental back-arcs. Back-arc regions likely existed before the mid-Proterozoic, but would have been at even higher mantle temperatures; at temperatures >150 °C higher than present day, they may have featured the lower lithosphere 'peeling' off and delaminating into the mantle (*Chowdhury et al.*, 2017, 2020). At even higher mantle temperatures (∆>200–250 °C), most geodynamic modelling indicates that subduction itself was inhibited (*Sizova et al.*, 2010; *Perchuk et al.*, 2019)(c.f. *Weller et al.*, 2019); these temperatures correlate to the early Archean, for which geodynamics and the geological record are vigorously debated (e.g. *Windley et al.*, 2021; *Ivan et al.*, 2022).

Although we argue the mid-Proterozoic magmatic and metamorphic record is a natural consequence of secular mantle cooling, the trends in geochemistry are not simply linear, in fact, the preceding late Archean to early Paleoproterozoic displays many similarities to the Phanerozoic. The cause of this requires more investigation, but the abundance of high Sr/Y and high La/Yb signatures prior to the mid-Proterozoic imply that magma formation was occurring under higher pressure (thicker crust) conditions on average. This, and the abundance of magnesian rather than ferroan compositions, implies that hot and dry magma generation in back-arcs was not as dominant before the mid-Proterozoic as it was during this period. The loci of magmatism have evidently changed through time, despite the fact that back-arc type settings may have existed since at least the Mesoarchean. Although much work has focused on the origin of Archean TTGs, we suggest that further geodynamic numerical modelling could be aimed at a more holistic view of magmatism created during lithospheric convergence at a range of mantle potential temperatures.

The felsic compositional record suggests a relatively rapid transition into the mid-Proterozoic geodynamic regime at 1.9 Ga; however, we suggest this is a corollary of several effects: 1) the scant geological record during Earth's tectono-magmatic lull at 2.3 Ga (*Condie et al.*, 2022); 2) a period of diverse orogenesis (i.e. wide-ranging P-T conditions) during the amalgamation of Columbia, presumably representing heterogeneity in ambient mantle temperature as well a network of both accretionary and collisional orogenic belts; 3) the onset of a sustained global subduction network between 2.5 and 2 Ga (*Condie*, 2021; *Brown et al.*, 2022); 4) a potential mantle overturn event at ca. 2 Ga, perturbing the steady-state geological record (*Condie et al.*, 2022); and 5) the dominance of accretionary orogenesis and lack of collisional orogenesis in the 1.7–1.1 Ga period (*Roberts et al.*, 2022). Therefore, although the geochemical record features apparent dramatic shifts, we argue that changes in convergent margin geodynamics would have been protracted transitions. *Roberts et al.* (2022) argued that the mid-Proterozoic was host to a transitional phase of geodynamics, influenced by both secular mantle cooling and the long tenure and impartial break-up of the Columbia supercontinent. Our present model builds on this argument - hot, wide, continental back-arcs located along margins of the Columbia supercontinent provide a mechanism to generate the observed magmatic and metamorphic record of this period.

In the Neoproterozoic, continued secular mantle cooling would allow geodynamics to further evolve such that deep subduction of continental lithosphere was possible at convergent margins (*Condie*, 2021; *Brown et al.*, 2022). Back-arc mantle temperatures would also have cooled down due to secular mantle cooling, and by the Phanerozoic, the geodynamics of subduction zone margins were likely similar to present day.

8 Conclusions

Elevated mantle temperatures in the mid-Proterozoic led to geodynamics with subtle but critical differences to those of the Phanerozoic - wider continental back-arc regions with extensive decompression melting of asthenosphere above the melt extraction threshold, leading to widespread basaltic underplating, and a greater volume and spatial extent of ferroan magmatism, including AMC suites, inboard of the volcanic arc. Our model explains the prevalence of seemingly 'anorogenic' or 'intraplate' granitoids within the mid-Proterozoic, and places them in the context of convergent margin activity. Hot back-arc crust and elevated geothermal gradients would lead to high temperatures being easily attained during continental collision, potentially explaining the abundance of high-temperature metamorphic terranes in the Mesoproterozoic. The formation of hot, wide, continental back-arcs does not necessarily require extra mantle heat derived from insulation under the Columbia supercontinent; therefore, although distinctive in many regards, the mid-Proterozoic geological record can be regarded as a natural consequence of secular mantle cooling and evolving lithospheric geodynamics.

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Author contributions

NR: conceptualisation of the ideas, data compilation, figure drafting and paper writing. **KC**: data compilation, paper writing and reviewing. **RM**: paper writing and reviewing. **CS**: paper writing and reviewing.

Data availability

Data and method associated with this paper are stored and accessible from Figshare: (https://figshare.com/s/ac88c402d35c624848cb).

Competing interests

The authors declare no competing interests.

Peer review

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References

Alonso-Perez, R., O. Müntener, and P. Ulmer (2009), Igneous garnet and amphibole fractionation in the roots of island arcs: experimental constraints on andesitic liquids, *Contributions to mineralogy and petrology. Beitrage zur Mineralogie und Petrologie*, *157*(4), 541–558, doi: 10.1007/s00410-008-0351-8.

Anderson, J. L., and J. Morrison (2005), Ilmenite, magnetite, and peraluminous mesoproterozoic anorogenic granites of laurentia and baltica, *Lithos*, *80*(1), 45–60, doi: 10.1016/j.lithos.2004.05.008.

Ashwal, L. D. (2010), The temporality of anorthosites, *Canadian mineralogist*, *48*(4), 711–728, doi: 10.3749/canmin.48.4.711.

Ashwal, L. D., and G. M. Bybee (2017), Crustal evolution and the temporality of anorthosites, *Earth-Science Reviews*, *173*, 307–330, doi: 10.1016/j.earscirev.2017.09.002.

Åhäll, K.-I., J. N. Connelly, and T. S. Brewer (2000), Episodic rapakivi magmatism due to distal orogenesis?: Correlation of 1.69–1.50 ga orogenic and inboard, "anorogenic" events in the baltic shield, *Geology*, *28*(9), 823–826, doi: 10.1130/0091-7613(2000)28<823:ERMDTD>2.0.CO;2.

Bickford, M. E., W. R. Van Schmus, K. E. Karlstrom, P. A. Mueller, and G. D. Kamenov (2015), Mesoproterozoic-trans-Laurentian magmatism: A synthesis of continent-wide age distributions, new SIMS U–Pb ages, zircon saturation temperatures, and hf and nd isotopic compositions, *Precambrian research*, *265*, 286–312, doi: 10.1016/j.precamres.2014.11.024.

Brown, M., and T. Johnson (2018), Secular change in metamorphism and the onset of global plate tectonics, *The American mineralogist*, *103*(2), 181–196, doi: 10.2138/am-2018-6166.

Brown, M., and T. Johnson (2019), Time's arrow, time's cycle: Granulite metamorphism and geodynamics, *Mineralogical magazine*, *83*(3), 323–338, doi: 10.1180/mgm.2019.19.

Brown, M., T. Johnson, and C. J. Spencer (2022), Secular changes in metamorphism and metamorphic cooling rates track the evolving plate-tectonic regime on earth, *Journal of the Geological Society*, *179*(5), jgs2022–050, doi: 10.1144/jgs2022-050.

Capitanio, F. A., O. Nebel, P. A. Cawood, R. F. Weinberg, and F. Clos (2019), Lithosphere differentiation in the early earth controls archean tectonics, *Earth and planetary science letters*, *525*, 115,755, doi: 10.1016/j.epsl.2019.115755.

Cawood, P. A., and C. J. Hawkesworth (2014), Earth's middle age, *Geology*, *42*(6), 503–506, doi: 10.1130/g35402.1.

Cawood, P. A., A. Kröner, W. J. Collins, T. M. Kusky, W. D. Mooney, and B. F. Windley (2009), Accretionary orogens through earth history, *Geological Society, London, Special Publications*, *318*(1), 1–36, doi: 10.1144/SP318.1.

Cawood, P. A., C. J. Hawkesworth, S. A. Pisarevsky, B. Dhuime, F. A. Capitanio, and O. Nebel (2018), Geological archive of the onset of plate tectonics, *Philosophical transactions. Series A, Mathematical, physical, and engineering sciences*, *376*(2132), 20170,405, doi: 10.1098/rsta.2017.0405.

Chowdhury, P., T. Gerya, and S. Chakraborty (2017), Emergence of silicic continents as the lower crust peels off on a hot plate-tectonic earth, *Nature geoscience*, *10*(9), 698–703, doi: 10.1038/ngeo3010.

Chowdhury, P., S. Chakraborty, T. V. Gerya, P. A. Cawood, and F. A. Capitanio (2020), Peel-back controlled lithospheric convergence explains the secular transitions in archean metamorphism and magmatism, *Earth and planetary science letters*, *538*, 116,224, doi: 10.1016/j.epsl.2020.116224.

Collins, W. J., S. D. Beams, A. J. R. White, and B. W. Chappell (1982), Nature and origin of a-type granites with particular reference to southeastern australia, *Contributions to mineralogy and petrology. Beitrage zur Mineralogie und Petrologie*, *80*(2), 189–200, doi: 10.1007/bf00374895.

Collins, W. J., H.-Q. Huang, P. Bowden, and A. I. S. Kemp (2020), Repeated S–I–A-type granite trilogy in the lachlan orogen and geochemical contrasts with a-type granites in nigeria: implications for petrogenesis and tectonic discrimination, *Geological Society, London, Special Publications*, *491*(1), 53–76, doi: 10.1144/SP491-2018-159.

Condie, K. C. (2021), Two major transitions in earth history: Evidence of two lithospheric strength thresholds, *The Journal of geology*, *129*(5), 455–473, doi: 10.1086/711141.

Condie, K. C., S. A. Pisarevsky, and S. J. Puetz (2021), LIPs, orogens and supercontinents: The ongoing saga, *Gondwana Research*, *96*, 105–121, doi: 10.1016/j.gr.2021.05.002.

Condie, K. C., S. A. Pisarevsky, S. J. Puetz, C. J. Spencer, W. Teixeira, and F. Meira Faleiros (2022), A reappraisal of the global tectono-magmatic lull at ∼2.3 ga, *Precambrian research*, *376*(106690), 106,690, doi: 10.1016/j.precamres.2022.106690.

Currie, C. A., R. S. Huismans, and C. Beaumont (2008), Thinning of continental backarc lithosphere by flow-induced gravitational instability, *Earth and planetary science letters*, *269*(3), 436–447, doi: 10.1016/j.epsl.2008.02.037.

DeCelles, P. G., M. N. Ducea, P. Kapp, and G. Zandt (2009), Cyclicity in cordilleran orogenic systems, *Nature geoscience*, *2*(4), 251–257, doi: 10.1038/ngeo469.

Fischer, R., and T. Gerya (2016), Regimes of subduction and lithospheric dynamics in the precambrian: 3D thermomechanical modelling, *Gondwana Research*, *37*, 53–70, doi: 10.1016/j.gr.2016.06.002.

Frost, B. R., C. G. Barnes, W. J. Collins, R. J. Arculus, D. J. Ellis, and C. D. Frost (2001), A geochemical classification for granitic rocks, *Journal of Petrology*, *42*(11), 2033–2048, doi: 10.1093/petrology/42.11.2033.

Frost, C. D., and B. R. Frost (1997), Reduced rapakivi-type granites: The tholeiite connection, *Geology*, *25*(7), 647–650, doi: 10.1130/0091-7613(1997)025<0647:RRTGTT>2.3.CO;2.

Frost, C. D., and B. R. Frost (2010), On ferroan (a-type) granitoids: their compositional variability and modes of origin, *Journal of Petrology*, *52*(1), 39–53, doi: 10.1093/petrology/egq070.

Ganne, J., and X. Feng (2017), Primary magmas and mantle temperatures through time, *Geochemistry, Geophysics, Geosystems*, *18*(3), 872–888, doi: 10.1002/2016GC006787.

Gard, M., D. Hasterok, and J. A. Halpin (2019), Global whole-rock geochemical database compilation, *Earth system science data*, *11*(4), 1553–1566, doi: 10.5194/essd-11-1553-2019.

Haapala, I., and O. Tapani Rämö (1992), Tectonic setting and origin of the proterozoic rapakivi granites of southeastern fennoscandia, *Earth and environmental science transactions of the Royal Society of Edinburgh*, *83*(1-2), 165–171, doi: 10.1017/S0263593300007859.

Haschke, M., W. Siebel, A. Günther, and E. Scheuber (2002), Repeated crustal thickening and recycling during the andean orogeny in north chile (21°-26°s), *Journal of geophysical research*, *107*(B1), ECV 6–1–ECV 6–18, doi: 10.1029/2001jb000328.

Herzberg, C., K. Condie, and J. Korenaga (2010), Thermal history of the earth and its petrological expression, *Earth and planetary science letters*, *292*(1), 79–88, doi: 10.1016/j.epsl.2010.01.022.

Holder, R. M., D. R. Viete, M. Brown, and T. E. Johnson (2019), Metamorphism and the evolution of plate tectonics, *Nature*, *572*(7769), 378–381, doi: 10.1038/s41586-019-1462-2.

Hyndman, R. D. (2019), Origin of regional barrovian metamorphism in hot backarcs prior to orogeny deformation, *Geochemistry, Geophysics, Geosystems*, *20*(1), 460–469, doi: 10.1029/2018gc007650.

Hyndman, R. D., C. A. Currie, and S. P. Mazzotti (2005), Subduction zone backarcs, mobile belts, and orogenic heat, *GSA today: a publication of the Geological Society of America*, *15*(2), 4, doi: 10.1130/1052-5173(2005)15<4:szbmba>2.0.co;2.

Indares, A. (2020), Deciphering the metamorphic architecture and magmatic patterns of large hot orogens: Insights from the central grenville province, *Gondwana Research*, *80*, 385–409, doi: 10.1016/j.gr.2019.10.013.

Ivan, Z., K. Anthony I S, S. R Hugh, R. Daniela, K. Fawna, H. Johannes, J. Tim E, G. Klaus, W. Roberto F, V. Jeff D, M. Laure, and R. Sandra S (2022), Greenstone burial–exhumation cycles at the late archean transition to plate tectonics, *Nature communications*, *13*(1), 1–17, doi: 10.1038/s41467-022-35208-2.

Korhonen, F. J., and S. P. Johnson (2015), The role of radiogenic heat in prolonged intraplate reworking: The capricorn orogen explained?, *Earth and planetary science letters*, *428*, 22–32, doi: 10.1016/j.epsl.2015.06.039.

Landenberger, B., and W. J. Collins (1996), Derivation of a-type granites from a dehydrated charnockitic lower crust: Evidence from the chaelundi complex, eastern australia, *Journal of Petrology*, *37*(1), 145–170, doi: 10.1093/petrology/37.1.145.

Lenardic, A., L. Moresi, A. M. Jellinek, C. J. O'Neill, C. M. Cooper, and C. T. Lee (2011), Continents, supercontinents, mantle thermal mixing, and mantle thermal isolation: Theory, numerical simulations, and laboratory experiments, *Geochemistry, Geophysics, Geosystems*, *12*(10), doi: 10.1029/2011GC003663.

Liu, C., A. H. Knoll, and R. M. Hazen (2017), Geochemical and mineralogical evidence that rodinian assembly was unique, *Nature communications*, *8*(1), 1950, doi: 10.1038/s41467-017-02095-x.

Liu, C., S. E. Runyon, A. H. Knoll, and R. M. Hazen (2019), The same and not the same: Ore geology, mineralogy and geochemistry of rodinia assembly versus other supercontinents, *Earth-Science Reviews*, *196*, 102,860, doi: 10.1016/j.earscirev.2019.05.004.

Liu, M. (2001), Cenozoic extension and magmatism in the north american cordillera: the role of gravitational collapse, *Tectonophysics*, *342*(3), 407–433, doi: 10.1016/S0040-1951(01)00173-1.

Morrissey, L. J., M. Hand, T. Raimondo, and D. E. Kelsey (2014), Long-lived high-t , low-p granulite facies metamorphism in the arunta region, central australia, *Journal of Metamorphic Geology*, *32*(1), 25–47, doi: 10.1111/jmg.12056.

Moyen, J.-F. (2009), High Sr/Y and La/Yb ratios: The meaning of the "adakitic signature", *Lithos*, *112*(3-4), 556–574, doi: 10.1016/j.lithos.2009.04.001.

O'Neill, C., M. Brown, B. Schaefer, and J. A. Gazi (2022), Earth's anomalous middle-age magmatism driven by plate slowdown, *Scientific reports*, *12*(1), 10,460, doi: 10.1038/s41598-022-13885-9.

Palin, R. M., M. Santosh, W. Cao, S.-S. Li, D. Hernández-Uribe, and A. Parsons (2020), Secular change and the onset of plate tectonics on earth, *Earth-Science Reviews*, *207*, 103,172, doi: 10.1016/j.earscirev.2020.103172.

Perchuk, A. L., V. S. Zakharov, T. V. Gerya, and M. Brown (2019), Hotter mantle but colder subduction in the precambrian: What are the implications?, *Precambrian research*, *330*, 20–34, doi: 10.1016/j.precamres.2019.04.023.

Rämö, O. T., and I. Haapala (1995), One hundred years of rapakivi granite, *Mineralogy and Petrology*, *52*(3), 129–185, doi: 10.1007/BF01163243.

Roberts, N. M. W., J. Salminen, Å. Johansson, R. N. Mitchell, R. M. Palin, K. C. Condie, and C. J. Spencer (2022), On the enigmatic mid-proterozoic: Single-lid versus plate tectonics, *Earth and planetary science letters*, *594*, 117,749, doi: 10.1016/j.epsl.2022.117749.

Sizova, E., T. Gerya, M. Brown, and L. L. Perchuk (2010), Subduction styles in the precambrian: Insight from numerical experiments, *Lithos*, *116*(3), 209–229, doi: 10.1016/j.lithos.2009.05.028.

Sizova, E., T. Gerya, and M. Brown (2014), Contrasting styles of phanerozoic and precambrian continental collision, *Gondwana Research*, *25*(2), 522–545, doi: 10.1016/j.gr.2012.12.011.

Slagstad, T., N. M. W. Roberts, N. Coint, I. Høy, S. Sauer, C. L. Kirkland, M. Marker, T. S. Røhr, I. H. C. Henderson, M. A. Stormoen, Ø. Skår, B. E. Sørensen, and G. Bybee (2018), Magma-driven, high-grade metamorphism in the sveconorwegian province, southwest norway, during the terminal stages of fennoscandian shield evolution, *Geosphere*, *14*(2), 861–882, doi: 10.1130/GES01565.1.

Slagstad, T., I. H. C. Henderson, N. M. W. Roberts, E. V. Kulakov, M. Ganerød, C. L. Kirkland, B. Dalslåen, R. A. Creaser, and N. Coint (2022), Anorthosite formation and emplacement coupled with differential tectonic exhumation of ultrahigh-temperature rocks in a sveconorwegian continental back-arc setting, *Precambrian research*, *376*, 106,695, doi: 10.1016/j.precamres.2022.106695.

Sobolev, S. V., and A. Y. Babeyko (2005), What drives orogeny in the andes?, *Geology*, *33*(8), 617–620, doi: 10.1130/g21557ar.1.

Spencer, C. J., R. N. Mitchell, and M. Brown (2021), Enigmatic mid-proterozoic orogens: Hot, thin, and low, *Geophysical research letters*, *48*(16), doi: 10.1029/2021gl093312.

Stern, R. (2020), The mesoproterozoic single-lid tectonic episode: Prelude to modern plate tectonics, *GSA today: a publication of the Geological Society of America*, *30*(12), 4–10, doi: 10.1130/gsatg480a.1.

Tamblyn, R., D. Hasterok, M. Hand, and M. Gard (2022), Mantle heating at ca. 2 ga by continental insulation: Evidence from granites and eclogites, *Geology*, *50*(1), 91–95, doi: 10.1130/G49288.1.

Vigneresse, J. L. (2005), The specific case of the Mid-Proterozoic rapakivi granites and associated suite within the context of the columbia supercontinent, *Precambrian research*, *137*(1), 1–34, doi: 10.1016/j.precamres.2005.01.001.

Vogt, K., T. V. Gerya, and A. Castro (2012), Crustal growth at active continental margins: Numerical modeling, *Physics of the Earth and Planetary Interiors*, *192-193*, 1–20, doi: 10.1016/j.pepi.2011.12.003.

Weller, O. M., A. Copley, W. G. R. Miller, R. M. Palin, and B. Dyck (2019), The relationship between mantle potential temperature and oceanic lithosphere buoyancy, *Earth and planetary science letters*, *518*, 86–99, doi: 10.1016/j.epsl.2019.05.005.

Windley, B. F., T. Kusky, and A. Polat (2021), Onset of plate tectonics by the eoarchean, *Precambrian research*, *352*, 105,980, doi: 10.1016/j.precamres.2020.105980.

Zou, Y., R. N. Mitchell, X. Chu, M. Brown, J. Jiang, Q. Li, L. Zhao, and M. Zhai (2023), Surface evolution during the mid-proterozoic stalled by mantle warming under Columbia–Rodinia, *Earth and planetary science letters*, *607*, 118,055, doi: 10.1016/j.epsl.2023.118055.